Occulting Ozone Observatory (O_3) a briefing to the NAS EOS-1 Panel

Doug Lisman, Jet Propulsion Laboratory, California Institute of Technology

Stuart Shaklan, Jet Propulsion Laboratory, California Institute of Technology

Edward Schwieterman, University of California Riverside

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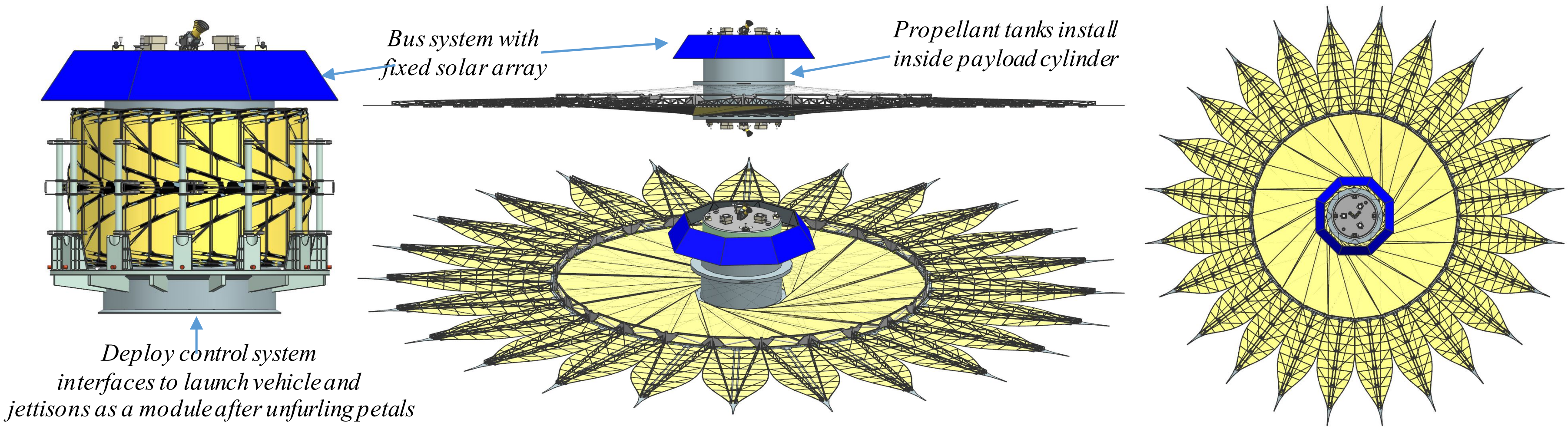
Introduction

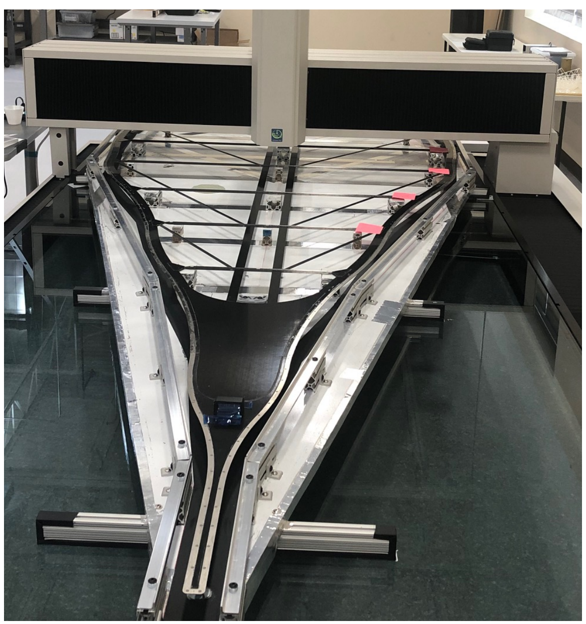
- **O_3 is a small starshade mission with focused science objectives that:**
  - Images previously undetectable planets, including rocky HZ planets and, after multiple observations, constrains their orbit and size to inform planetary system diversity and exozodi levels
  - Detects the likely presence (not abundance) of O_3 at rocky planets, as a robust proxy for O_2, although Venus has other NUV absorbers and to confirm a biologic origin requires a follow-on mission
  - Detects the likely presence (not slope) of Rayleigh scattering at larger gas planets
- **Prominent low-wavelength spectral features yield smaller telescopes and starshades**
  - The mission detailed here operates a 16-m starshade at 16-Mm from a shared and co-launched 1-m telescope (notionally CASTOR, a CSA study mission) with excellent retarget agility and low ΔV
  - The exact telescope remains flexible, with separate funding for diverse science desired, and the APC paper presents dedicated 60-cm and shared 1.5-m cases and the exact telescope
  –
- **A 3-yr. mission with dedicated search phase informs a target down-select to boost yield**
  - Yield is reported here for confirmed planets with constrained size and orbit and separately for the the select planets that are searched for ozone; additional unconfirmed candidates are not counted
- **Original 2009-10 O_3 study was rooted in a search for an elegant low-cost solution**
  - Led by David Spergel and Jeremy Kasdin (see Savransky et al 2010 and Thomson et al 2011)
  - Produced the new starshade architecture presented by multiple speakers at this meeting

Agenda

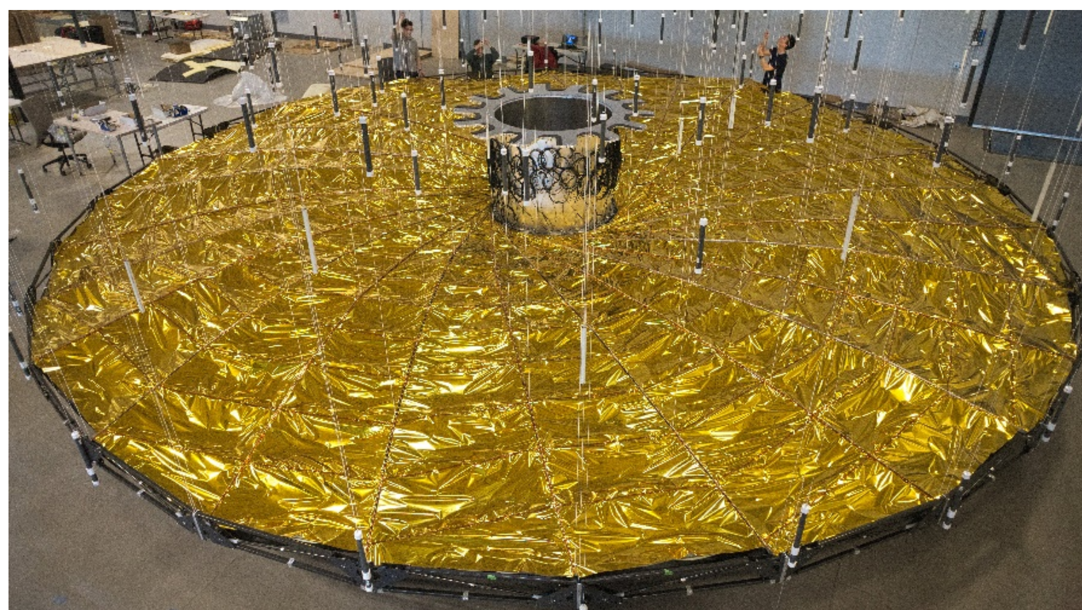
- Starshade design
- Instrument design
- Biosignature assessment
- Star list, observational strategy, expected yield
- Launch mass margin
- Likely mission cost range
- A small starshade SRM variant mission
- Conclusions

O_3 Starshade Design



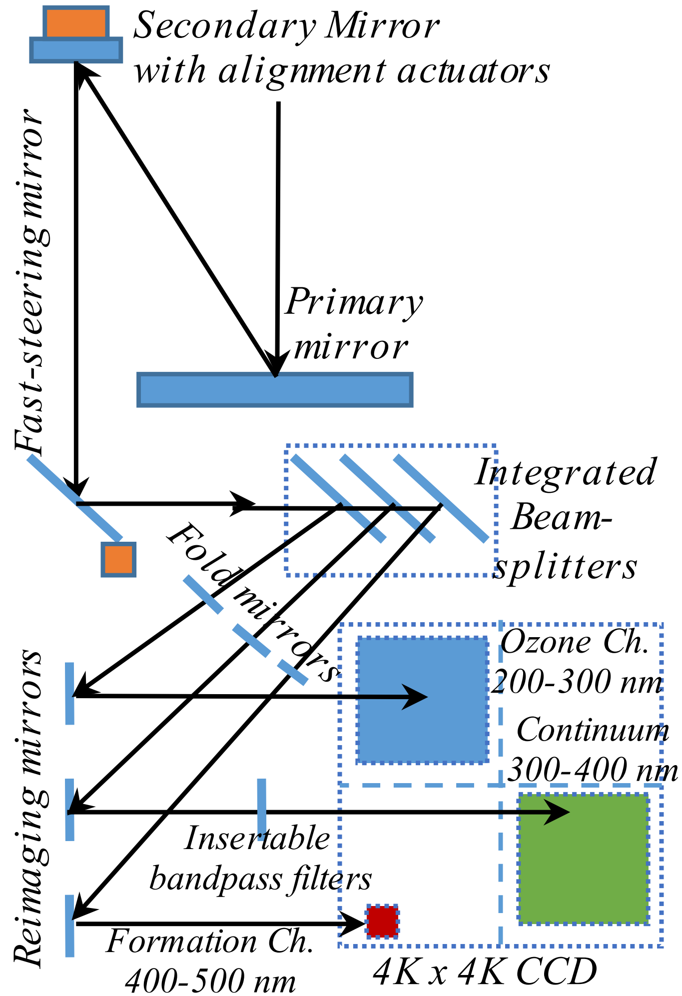


O_3 petal matches 4-m long pathfinder petal shown



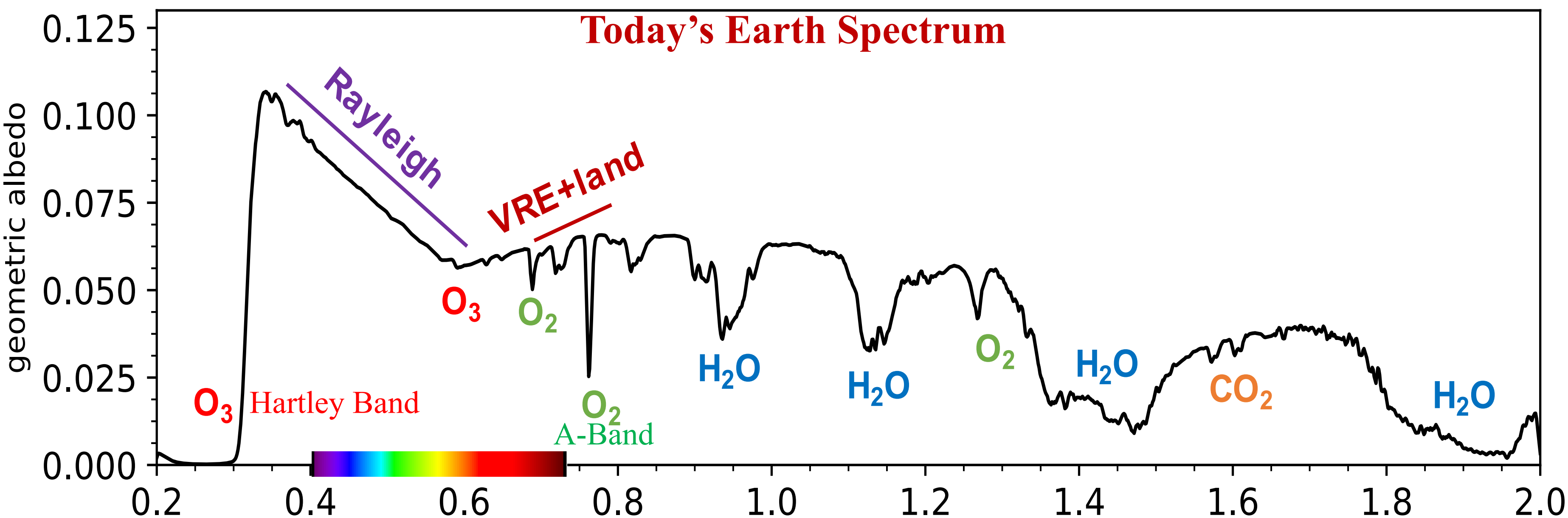
O_3 8-m disk compares to current 10-m disk prototype shown

O_3 Instrument Design



Ozone can be detected with a simple 2-channel photometer.
The 3rd channel shown here is for lateral formation sensing in out of band starlight.

Biosignature Comparison

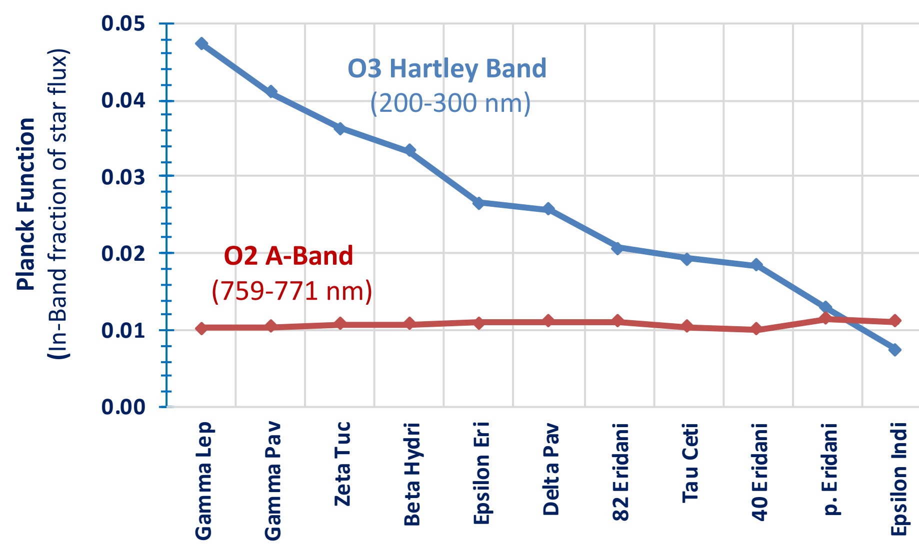


*O_2 A-Band detection requires SNR of **20.***
*O_3 Hartley Band detection requires SNR of **5**.*

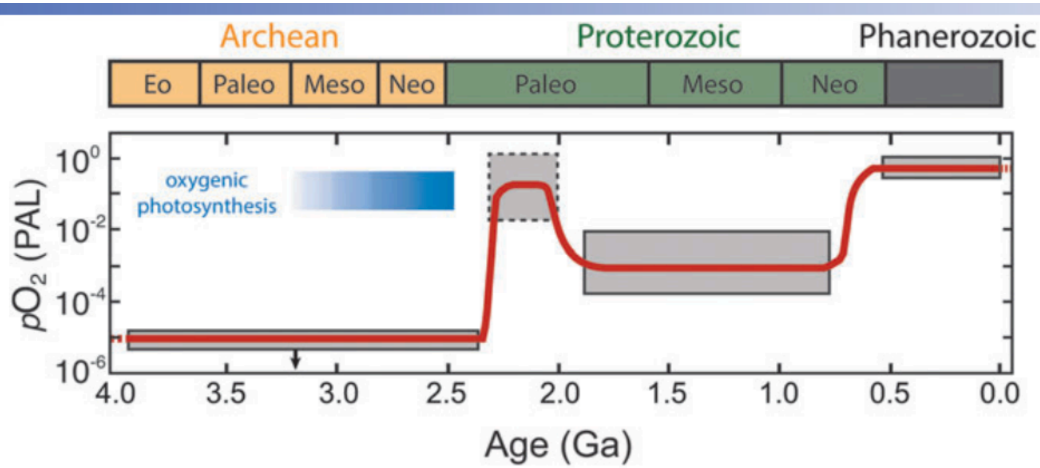
O_3 Hartley Band receives more of the integrated stellar flux vs. O_2 A-Band, except for the coldest target star Epsilon Indi

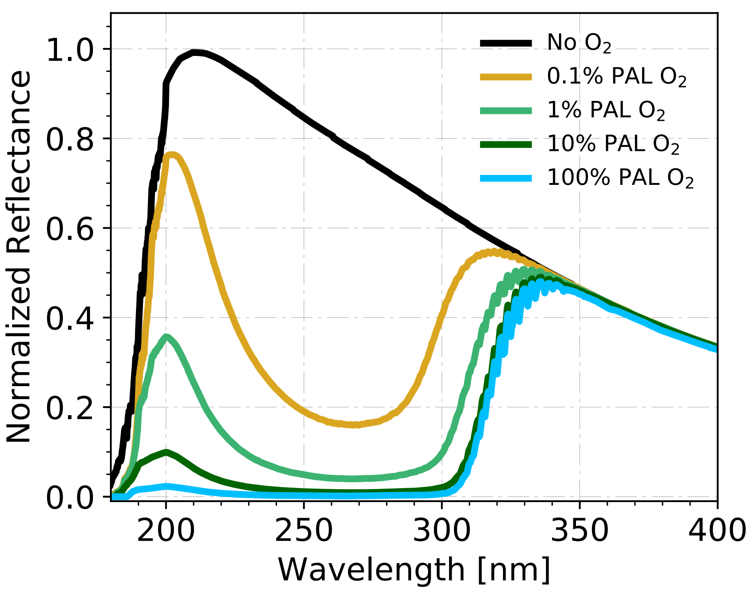
A given Fresnel number is achieved with a smaller starshade at shorter wavelengths

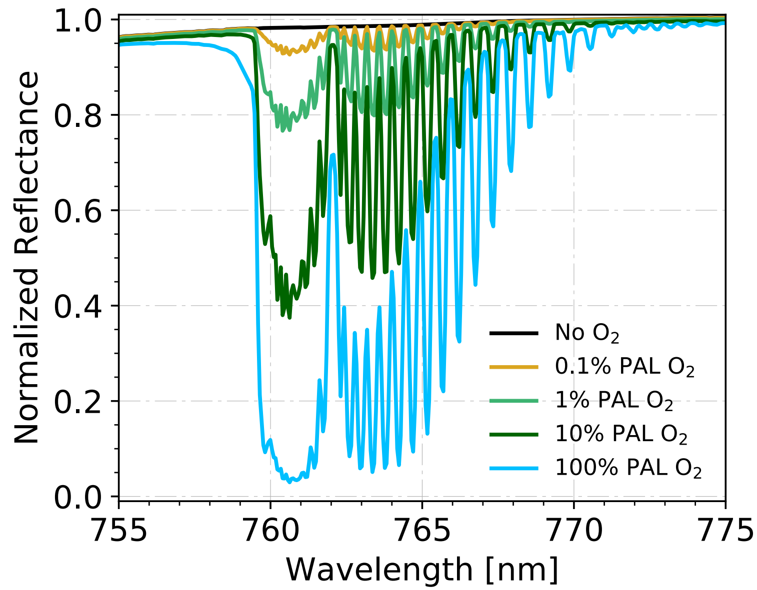
Starshade radius =√(F λ Z), where Z is telescope separation distance



Hartley Ozone Band – High Sensitivity O_2 Proxy



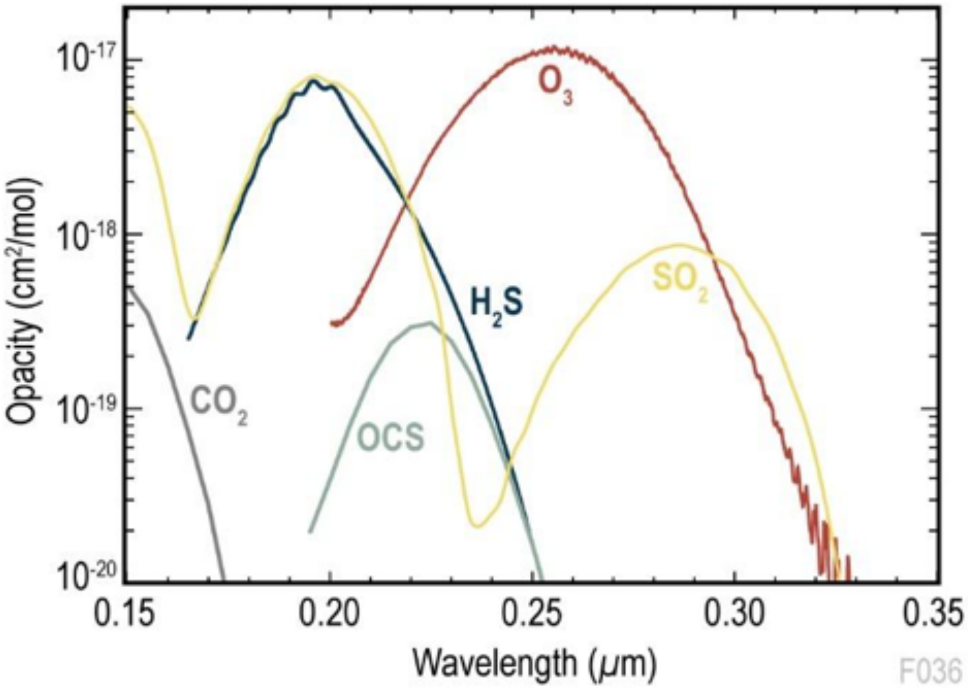




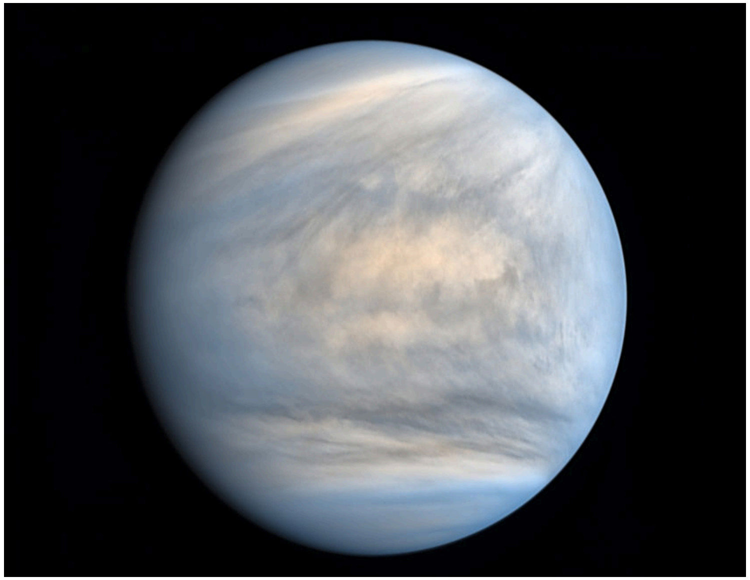
O_3 is a sensitive marker of Earth's photosynthetic biosphere & detectable over ~50% of Earth's history. O_2 has been a biosignature for only ~10-20% of Earth's history

Potential False Positives with Venus type planets

ExoPlanet Exploration Program



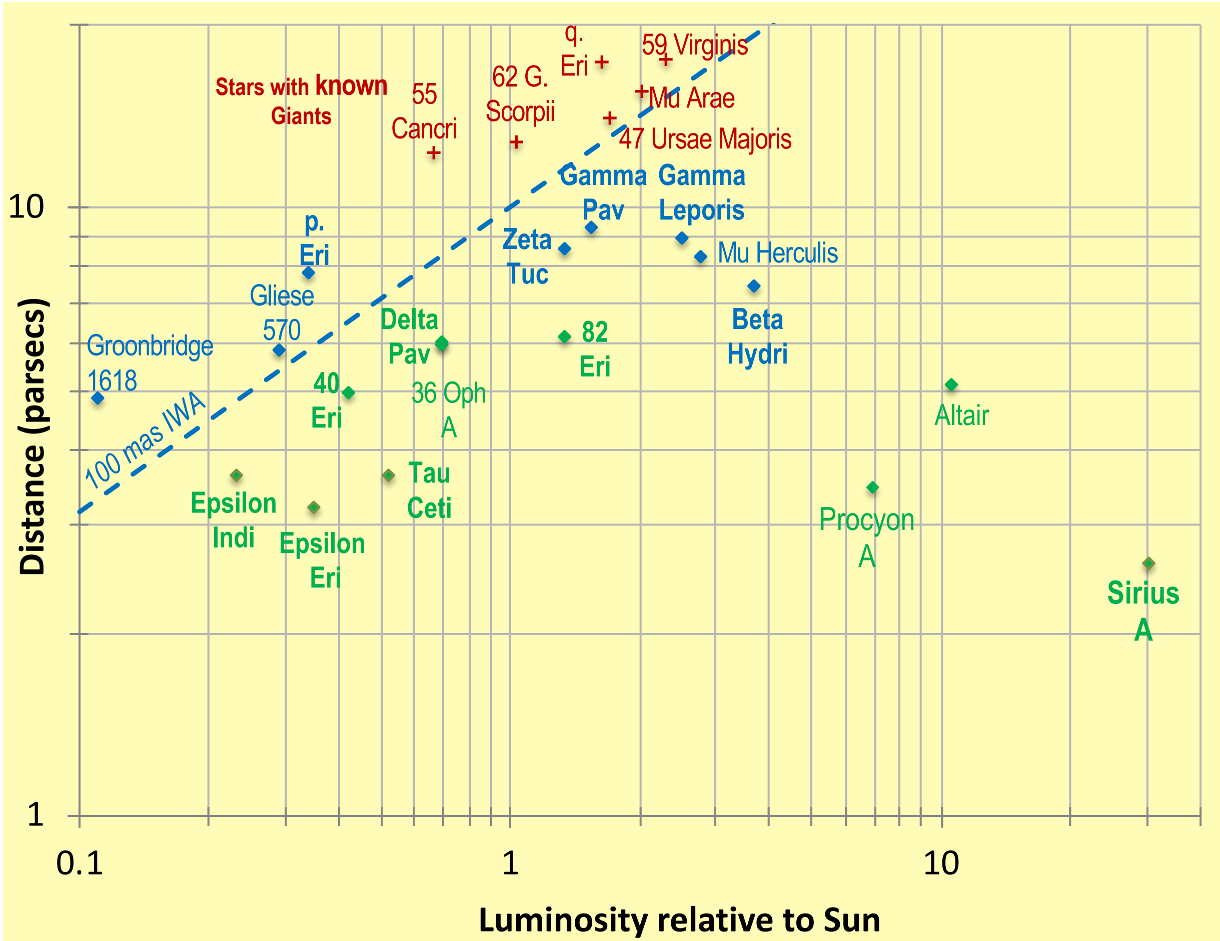
HabEx Interim Report



Ultraviolet Image of Venus, JAXA

Venus has other NUV absorber gases that cannot be disentangled by O_3

Star List



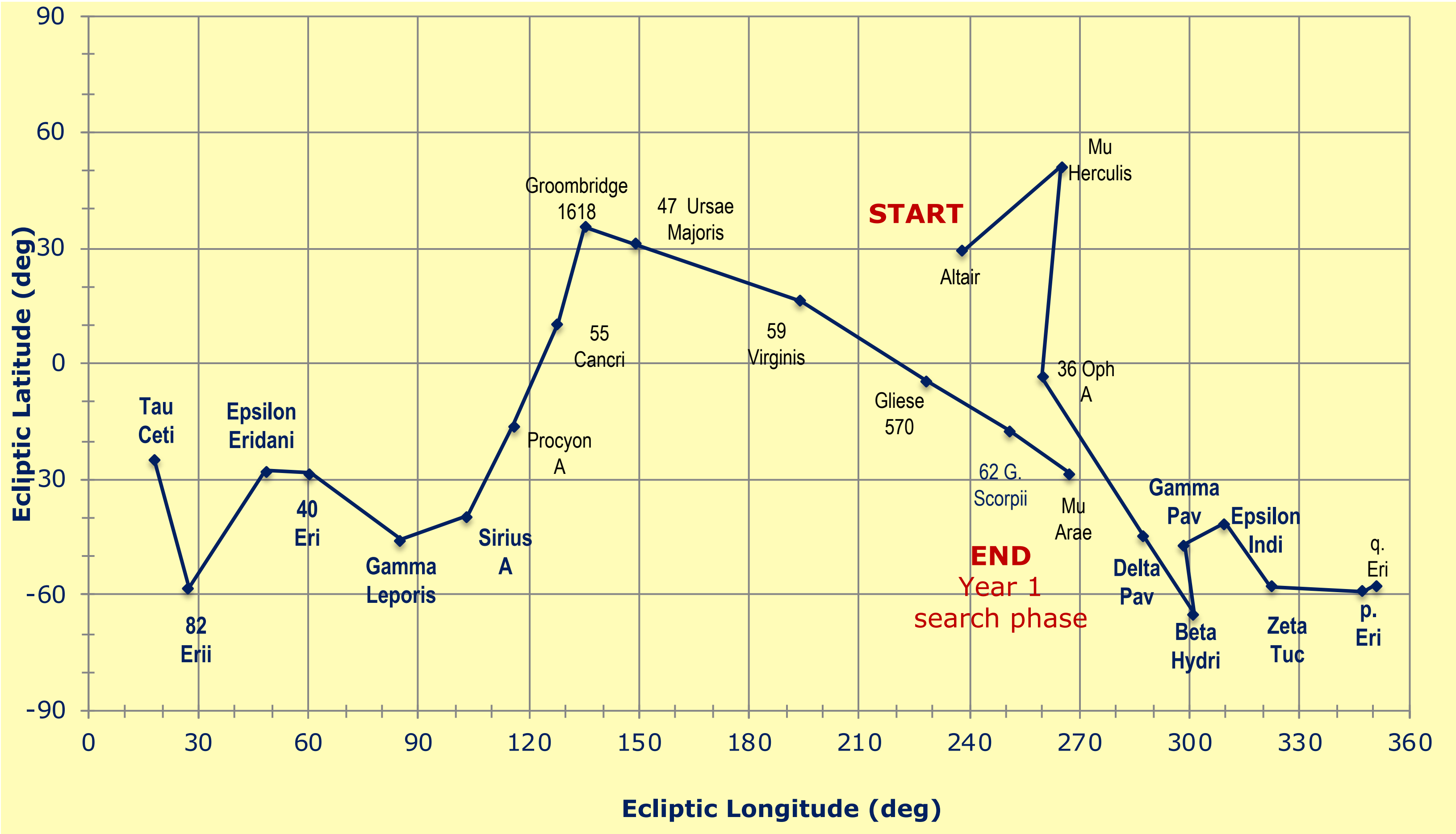
24 search phase target stars include 6 with 10 known Giant planets.
12 select stars for revisit phase are shown in bold type.
Exozodiacal light limits HZ observations to the closest stars.

Observation Strategy

- **Search all 24 stars in Year-1 with broadband imaging**
- **Down-select and observe each of 12 stars 4 times each over Years 2/3**
- **Search for Ozone/Rayleigh scatter with one 30-day observation at 8 select stars**

Year 1 Search Phase Observation Sequence

ExoPlanet Exploration Program

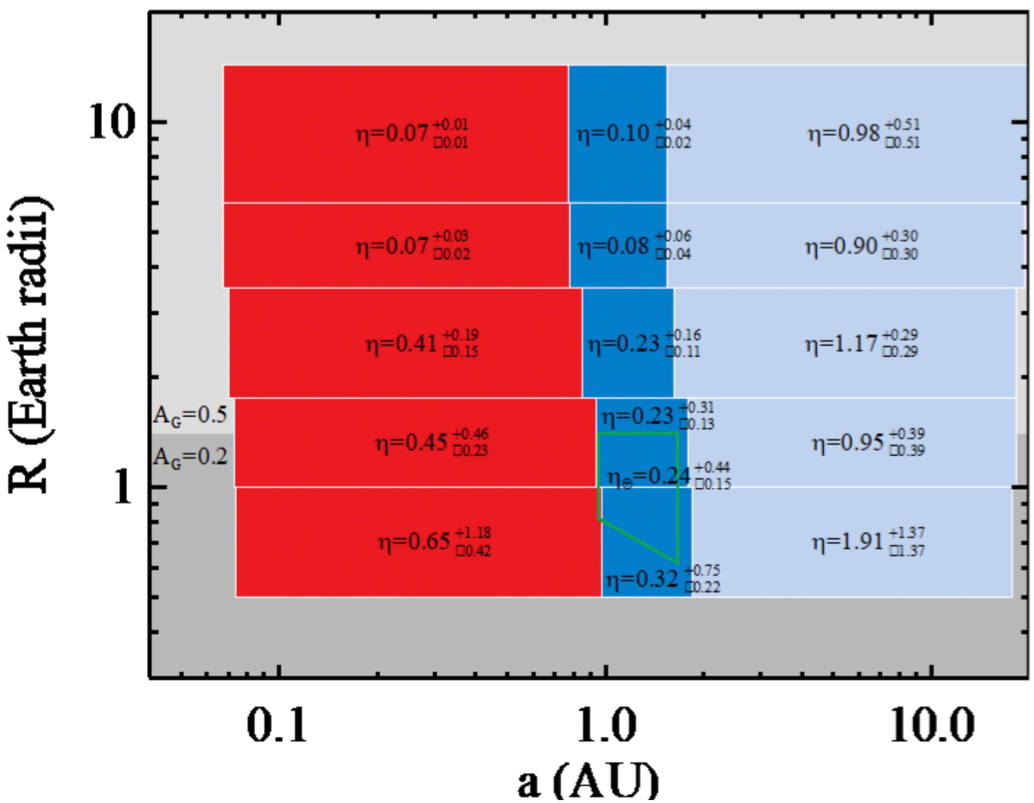


All 24 well distributed target stars can be searched in Year-1 with modest ΔV of ~300 m/s. Star-Sun angle constraint of 40° to 83° is preserved.

Yield Calculations

ExoPlanet Exploration Program

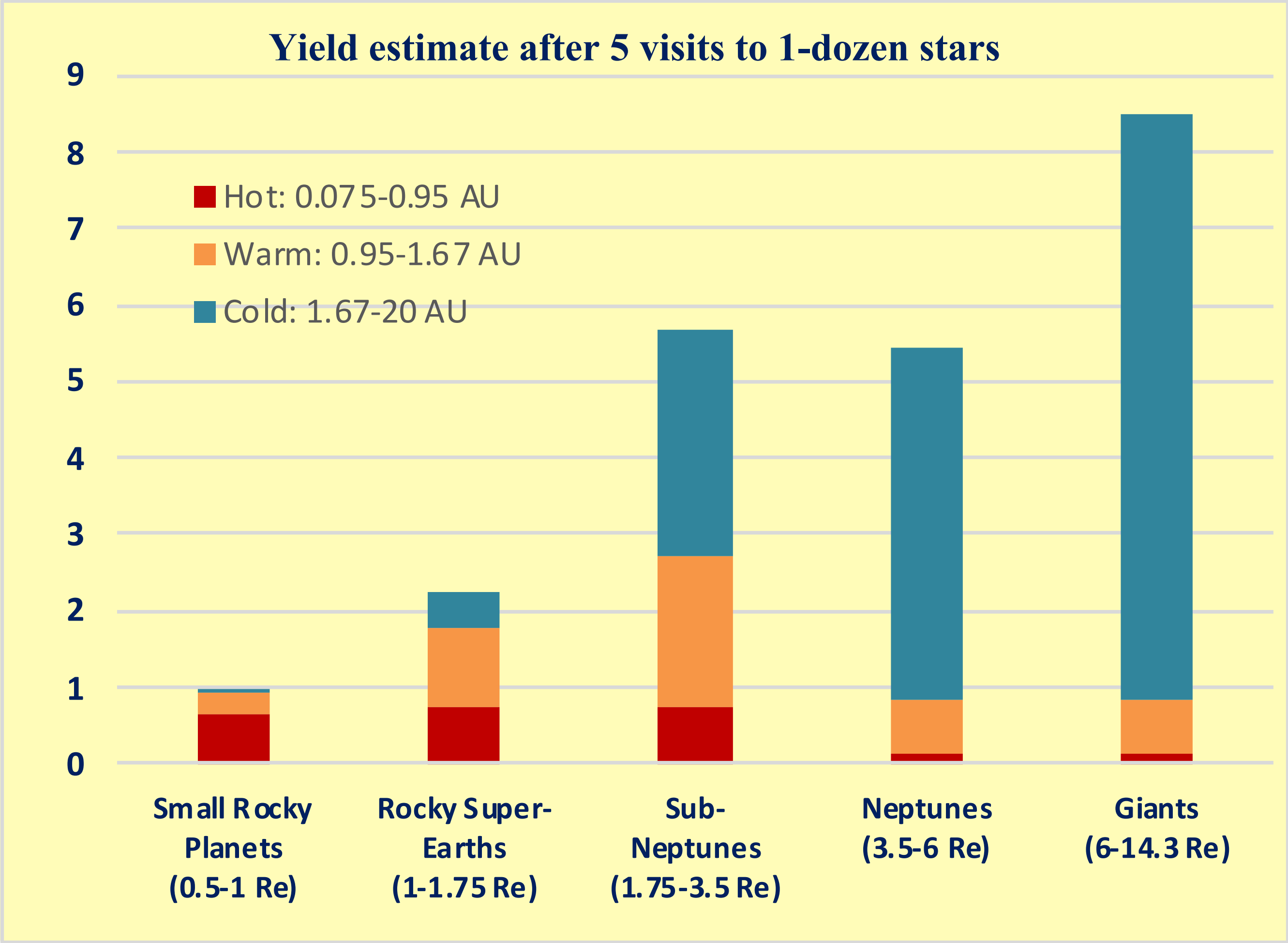
- Set exozodiacal light at median density level of 4 zodis, with 1 zodi at 22 mags/arc-sec^2
- Set planet sensitivity for SNR of 4 w.r.t. residual exozodi after calibration to 5% accuracy
- Compute search completeness for given planet size/albedo by numerically integrating the intercept of IWA, contrast curve (Lambertian phase function) over a given orbit size range
- Compute planet yield following the HabEx report, from which figure is lifted



Planet occurrence rates per SAG-13
Planet categories per Kopparapu et al 2018
Compiled by Chris Stark

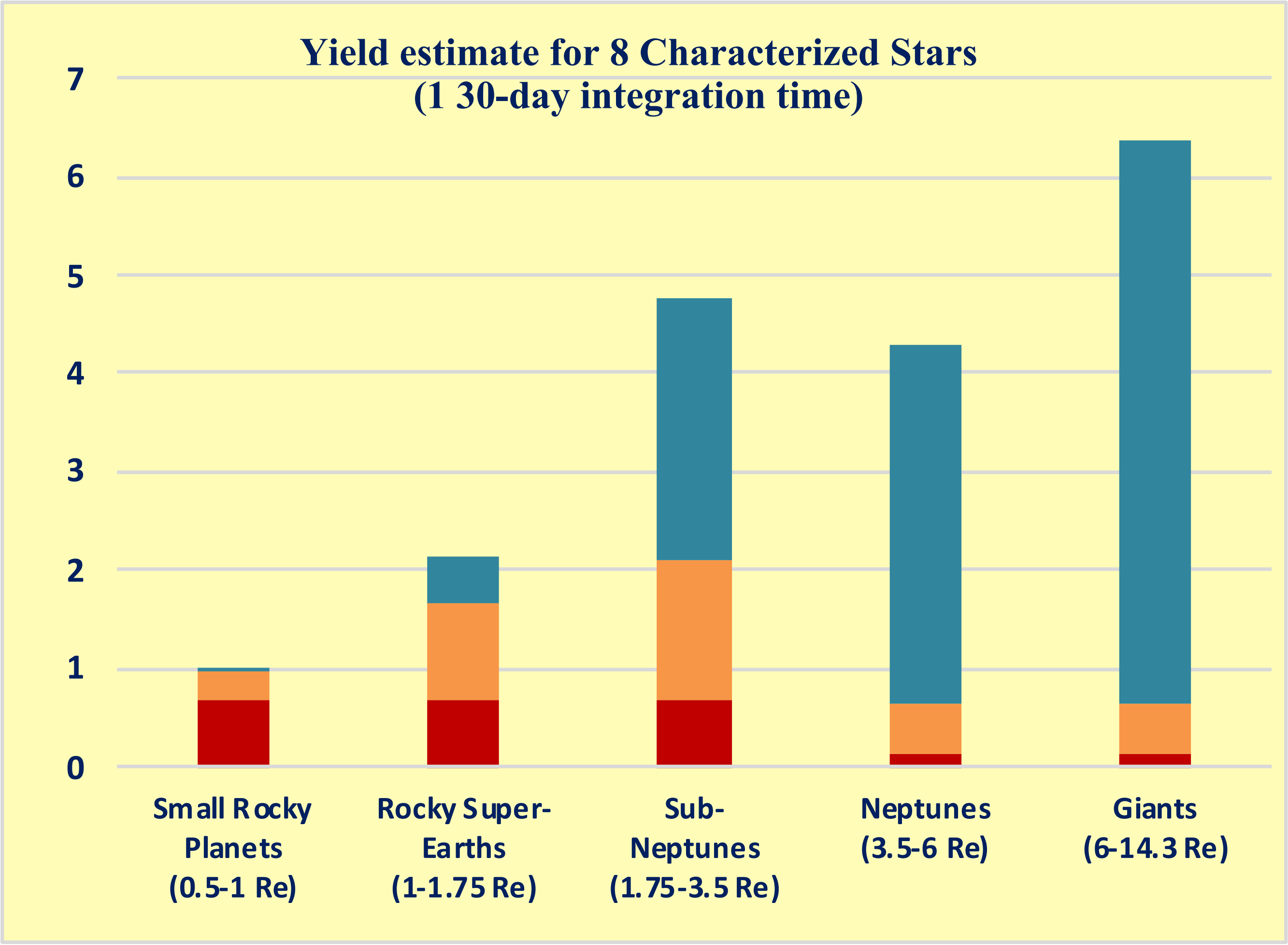
Here we approximate 3 fixed orbit ranges

Expected Planet Yield with constrained orbits and size



O_3 is expected to yield about 23 exoplanets with constrained orbits & size.
An additional ~15 unconfirmed or constrained detections are expected in Year-1.

Yield from 8 Characterized Planets



Launch Mass Margin

Element	Mass (kg)	Comments
16-m Starshade Payload CBE	410	8-m dia. Inner disk & 4-m long petals (Qty 24)
Starshade Bus System CBE	500	Deck mounted WISE bus with prop tanks inside starshade central cylinder
43% mass growth	390	Same as 30% margin against launch capacity
Max expected EOM starshade dry mass	**1300**	
Max propellant for 3 yr mission	1000	1600 m/s ΔV at 308s Isp with 6% residual prop
Max Telescope launch wet mass	800	
Max Starshade Deployment Control System	200	Module is jettisoned after deployment
Total Launch Mass	**3300**	
Launch Mass Capacity	3900	Falcon-9 direct to E-S L2
Extra launch mass margin	**600**	

O_3 has excess launch mass capacity that could be used for extended mission ΔV, and/or to carry a secondary payload

Expected Mission Cost Range

Element	Cost ($M)	Comments
16-m Starshade Payload	110	Includes TRL-6 campaign
Starshade Bus System	60	Fixed solar array, no science data, includes propulsion module
Telescope System	0	Contributed via mission partnership
Project Wrapper Cost	170	Includes 30% Reserves, Project Mgt., SE, MA, MOS/GDS, ATLO, Science
Total Flight System Cost	**340**	
Launch Service Cost	160	Falcon-9
Likely Nominal Cost	**500**	
Additional Cost Uncertainty	250	50% uncty due to brief JPL Foundry study & use of mass based cost models
Likely Maximum Cost	**750**	

O_3 mission cost is likely to be in the range of $500M to $750M

A SRM Variant Mission

- **The CGI switch to prism-based spectroscopy enables a small low-cost SRM variant mission, in similar fashion to O_3**
- **A slit and prism dedicated to the existing 425-552 nm imaging band supports Rayleigh scatter detection with a 22-m starshade at 22-Mm from WFIRST for 103-mas IWA**
- **A separate slit and prism (e.g., CGIs Band 3 covering 675-785 nm) can subsequently be used to search for O_2 & H_2O at *detected atmospheres* with separation increased to 31-Mm**
  - IWA grows to 146-mas vs. 103-mas SRM baseline and figure shows degraded search completeness
- **Can perform same O_3 DRM, but with ΔV that grows in proportion to separation**
- **Without a co-launched telescope the launch mass and cost is about the same as O_3**